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Remote Sensing of Ice Phenomena From Orbit by Signal Correlation of Multiple Receiver Responses

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ABSTRACT

This brief report explains and summarizes the method of signal correlation of microwave responses as applied to the measurement of Earth-surface ice temperatures from orbit. Ice temperatures are estimated by a correlation function that is derived from the processes of a forward stepwise correlator. Subsets of the post-detected outputs of microwave receiving channels are combined in a multivariate cross-correlation function which operates as a spatial filter and serves to improve the spatial resolution of the thermal gradients in ice structures. The correlator is designed to selectively identify the correlative components among the microwave responses and to strongly suppress or cancel the non-correlative components appearing in the post-detected outputs. From this philosophy, sidelobe contributions, radiances from atmospheric constituents, and manmade interference are significantly suppressed. The output of the cross correlation process yields a mathematical expression whose terms combine to serve as an estimator for the ice temperatures which are best reported by color imagery.

Because the spatial filtering processes operate to improve the spatial resolution in a manner that is not explained by diffraction-limited apertures and because the cross-correlation process further operates from microwave radiances covering a wide frequency band (several octaves in frequency), the spatial filtering process concept is consistent with the principle of a wideband, passive, synthetic-aperture receiver.

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DISCUSSION

Considered here is the method of signal correlation of multiple passive receiver responses as it is applied to remote sensing of ice from Earth orbit. The post-detected signal responses are combined by the processes of stepwise cross correlation to produce a statistical estimation of the thermal emission properties of ice. The receiver responses are in themselves narrow-band sampling intervals of a wideband frequency interval usually covering several octaves. The receivers and the sampled frequency interval as here discussed occur in the microwave region. The post-detected outputs from each of the participating receiver channels are processed by a stepwise cross correlator to produce a mathematical function that expresses the correlative association of the instantaneous signal variations arriving at the multichannel receiver's collecting aperture. The simultaneous radiances which emanate from the thermal gradients in the ice and occur in all participating receiver channels serve as the signal components that are cross correlated. The concept is illustrated in Figure 1. What Figure 1 proposes to show is that the post-detected signal components from many receiver channels which are in themselves relatively narrow-band, operate to sample the radiances (thermal gradients) from ice over a wide frequency interval which often may cover several octaves. In this case inputs for each receiver channel have been derived from a common antenna-feed-assembly and the beams so formed are collinear about a common viewing axis. In this manner the signal components in each receiver channel occur at the post-detected outputs at the same instant of time and at amplitudes that are consistent with the sensitivities and bandwidths of each individual receiver channel. An individual receiver channel is formed by any combination of its center frequency and polarization vector of the antenna.

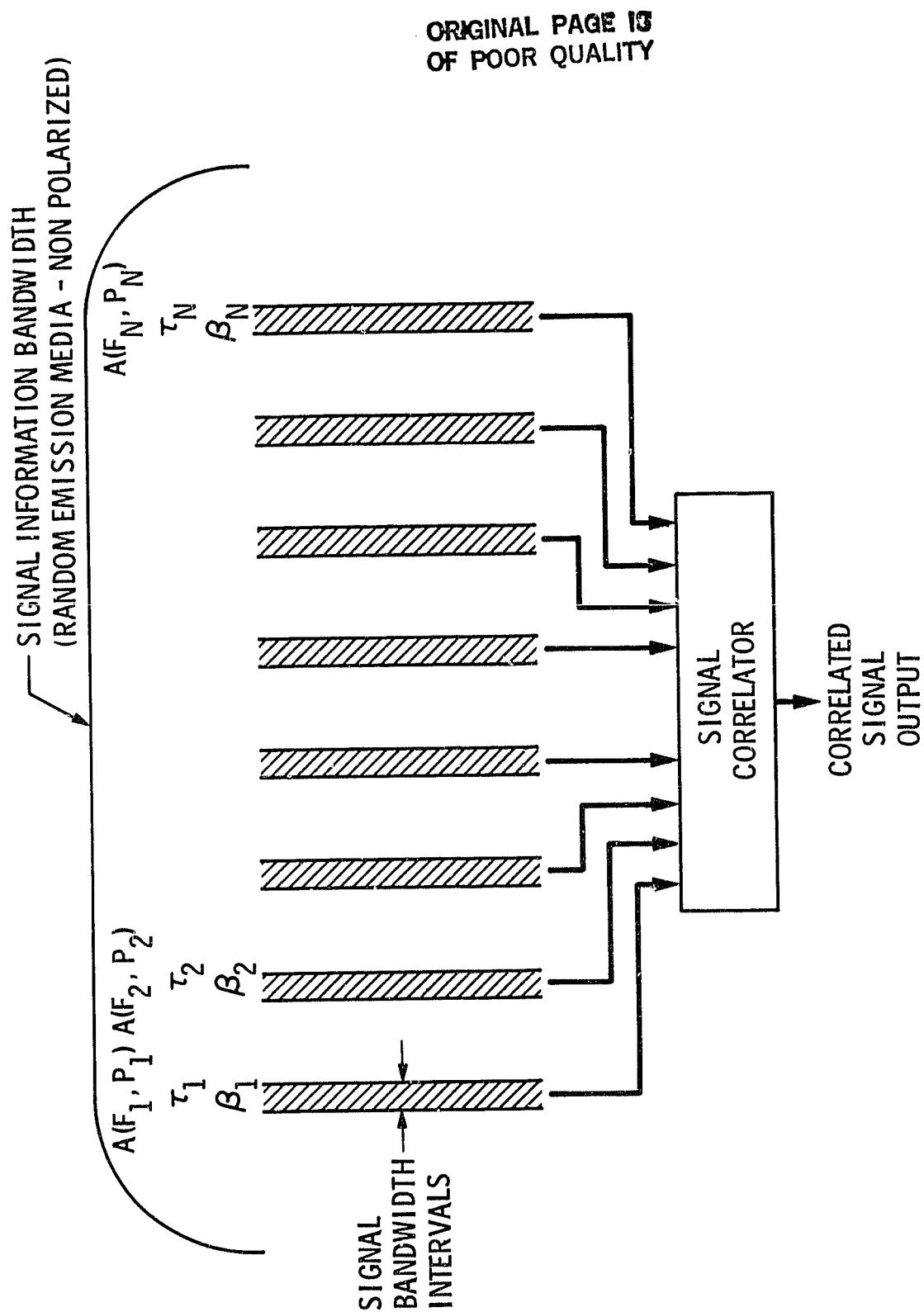


Fig. 1 Correlation receiver principle

The system concept of the correlator is illustrated in Figure 2, which shows that multiple receivers are combined into a cross correlator at their detected outputs. Each channel possesses an RF filter followed by a frequency conversion into a predetection IF bandwidth (β). The signal is detected, integrated (τ) and converted to digital counts which function as the output response for the channel. The multivariate cross correlator combines the correlative components of all the signals and produces a cross-correlation function which serves as a temperature estimator for the ice signatures. Notably, the antenna beams are all formed about the same pointing axis in a multifrequency feed horn which illuminates a common collecting aperture.

The intrinsic multiplicative properties of the cross correlator operate to narrow the correlated antenna response in a manner illustrated in Figure 3. Figure 3 demonstrates that the correlated channel response $F \begin{bmatrix} P \\ N \end{bmatrix} \Theta_N$ is narrower than the narrowest channel response, P_1 ; and also, in the correlated response, the sidelobes are importantly suppressed. The term predictor is substituted for receiver channel in Figure 3 to introduce the equivalent correlation terminology at this point. In fact, all mathematical terms, definitions, and statistical procedures employed hereafter are consistent with those defined and applied by Draper and Smith(1), and Bendel(2). The channel responses shown in Figure 3 may be viewed as predetection filter responses whose shapes are influenced by the antenna pattern, RF front-end component selectivity, and the predetection filter bandwidth itself. Actually, the multiplicative processes of the correlator are in effect performing a spatial-filtering operation whose final filter properties are determined by the choice of predictors entered into the correlator for processing. Depending also on the choice of predictors and their respective filter responses and their frequencies, the statistician maintains a useful (but imprecise) control of the spatial-filter width and the

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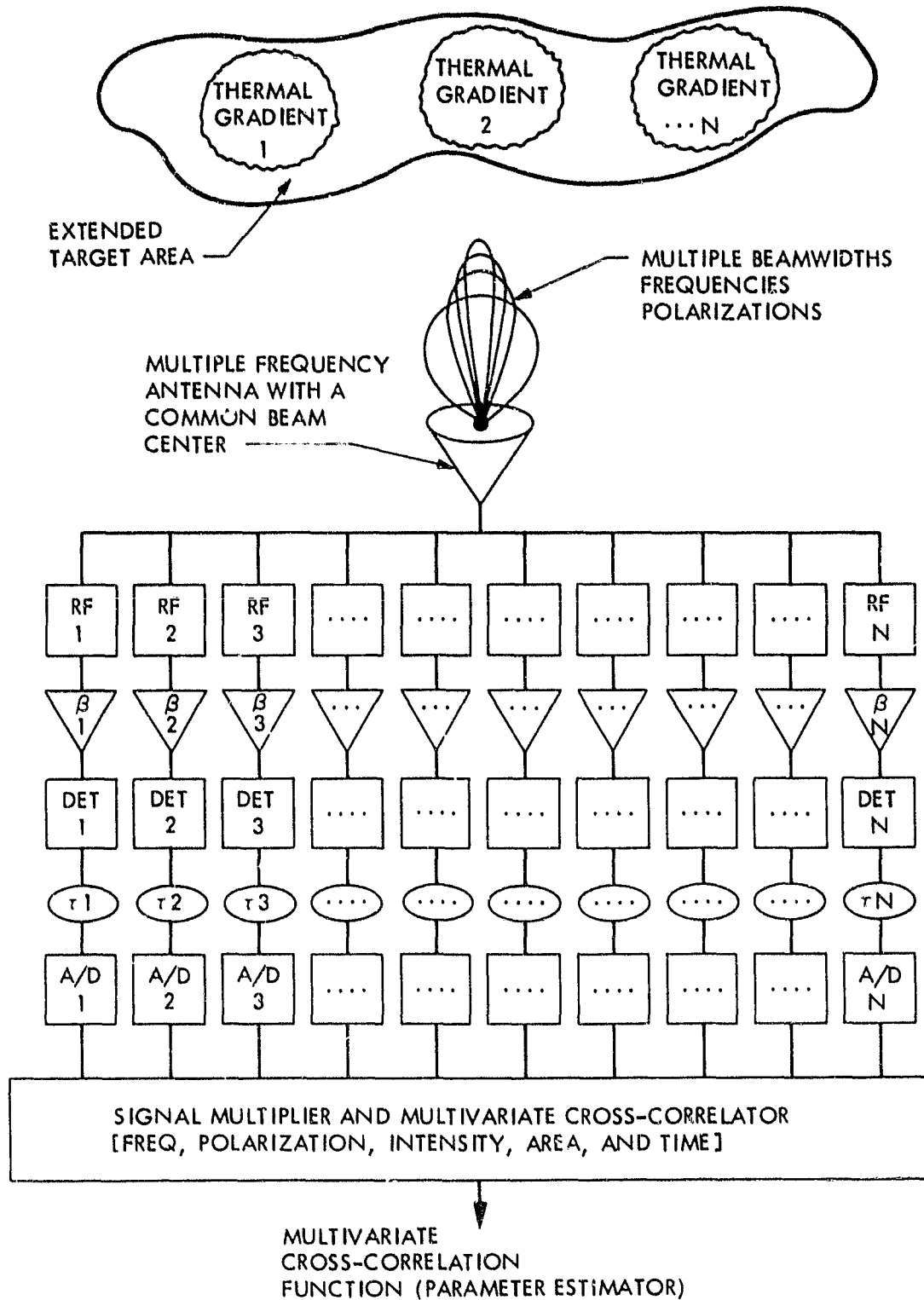


Fig. 2 Multivariate cross-correlator

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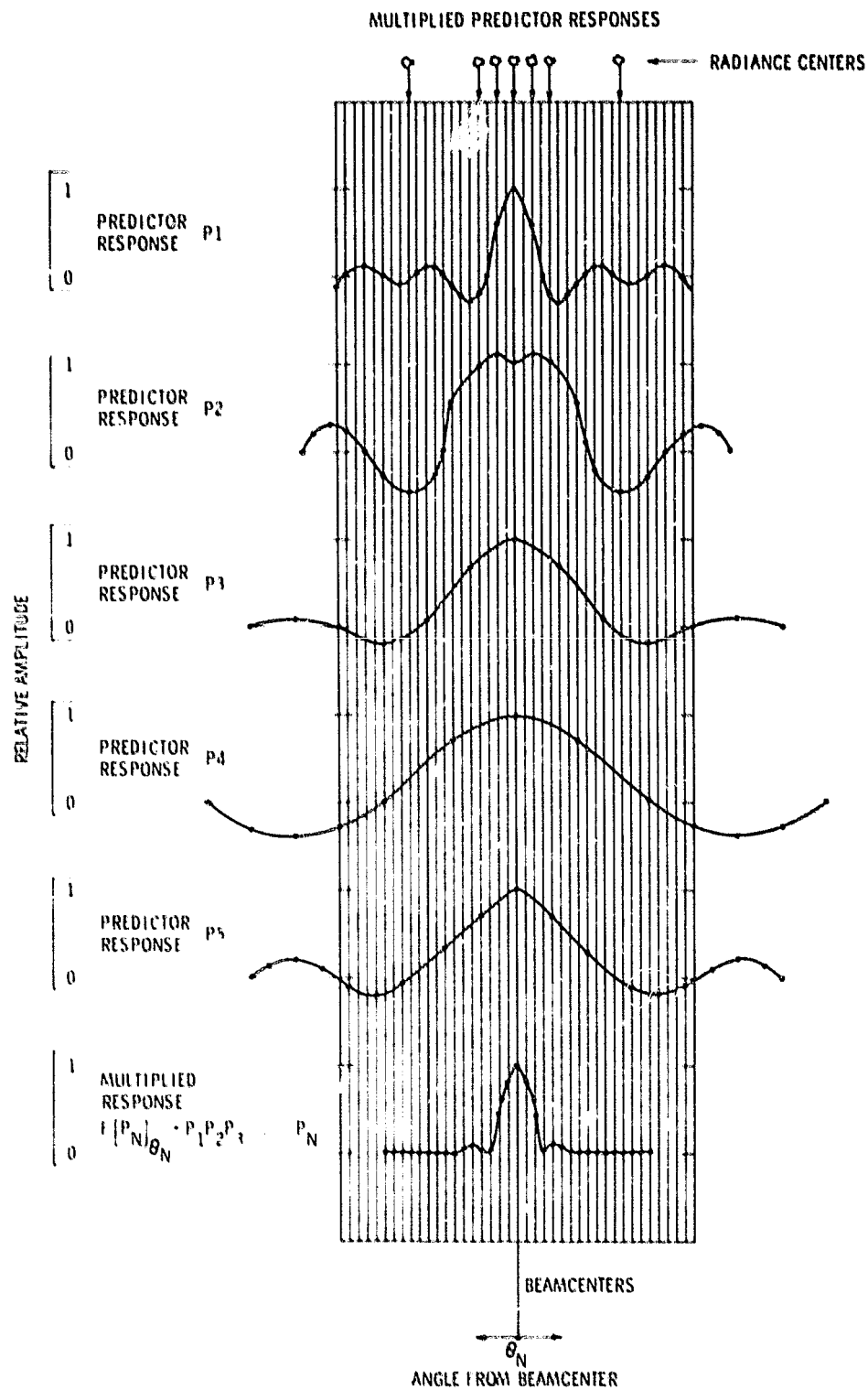


Fig. 3 Cross-correlated predictor responses (arbitrary post-detected outputs)

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penetration depths from which the microwave radiances are expected to emerge from the ice.

The multivariate cross correlator produces a statistical estimator for the thermal gradients across the ice for each footprint position as bounded by the geometrical limits of the ice image. The estimator is reasoned to produce a thermal image because the outcome of the cross correlation combines the independent contributions from frequencies and polarizations over a wide bandwidth and over several octaves in frequency. The correlation function (estimator) combines the radiances over a wide bandwidth and with randomized polarizations. The emissivities of the ice radiances are expected to be less than unity and constant for all frequencies and polarizations contained within the terms of the correlation function. For this reason, the estimate of the thermal gradients conforms with the definition of Graybody Radiation, which is known to be an imperfect blackbody radiator and is therefore intrinsically thermal in character.

SAMPLING MATRIX

The cross-correlation function is produced from a two-dimensional sampling matrix whose entries are taken as the digital counts from randomly-selected, collinear footprints for all predictors (frequencies and polarizations) over the areal extent of ice area to be imaged. More specifically, the column labels of the matrix identify the available predictors. Each row contains the respective numerical value of the digital counts for its corresponding predictor. The structure of the sampling matrix is illustrated in Table 1. In this particular matrix, additional predictors are formed from the primitives (i.e., linear terms). The sampling matrix is expected to contain the temperature range and character of the thermal gradients observed over the entire extent

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of the area to be imaged. The correlation function that is formed by the cross-correlation process may be applied to estimate the temperature of any footprint available for measurement within the limits of the randomly sampled area.

CORRELATION MATRIX

The correlative properties of the thermal gradients across the ice are epitomized in the correlation matrix shown in Table 2, which is computed from the sampling matrix (Table 1). The correlation matrix shows how every predictor is correlated with every other predictor. The tabular entries in the correlation matrix range from ± 1 where plus values denote positive correlation and negative values denote negative correlation. Both are equally important regardless of sign when they are the same magnitude. A correlation coefficient of 1 denotes that the post-detected outputs of the variates being compared are changing in perfect agreement -- a condition rarely encountered. The correlation matrix software is a standard product of most computer libraries. Experience has shown that the magnitudes of the correlation coefficients (R) computed from sampling matrices taken over the arctic and antarctic regions and for operating frequencies from C- to Ka-Band typically range from 0.85 to the high nineties. As to be expected the relative sizes of the beamwidths influence the magnitudes of the correlation coefficients.

The correlation matrix prognosticates the degree of success to be expected for forming robust correlation functions. High correlation coefficients among the higher frequency terms predict the possibility of achieving good spatial resolution with relatively few terms. Another useful function of the correlation matrix is to indicate the occurrence of extremely dense clouds or widespread rain within the sampled area. Poor correlation coefficients among the

Table 2

Correlation Matrix

	$P F_1, H_1 $	$P F_1, V_1 $	$P F_2, H_2 $	$P F_2, V_2 $...	$P F_N, H_N $	$P F_N, V_N $
$P F_1, H_1 $	1						
$P F_1, V_1 $	(R)	1					
$P F_2, H_2 $	(R)	(R)	1				
$P F_2, V_2 $	(R)	(R)	(R)	1			
\vdots					...		
$P F_N, H_N $	(R)	(R)	(R)	(R)		1	
$P F_N, V_N $	(R)	(R)	(R)	(R)		(R)	1

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P = POST-DETECTED POWER OUTPUT FOR EACH VARIATE

 F_N = CENTER FREQUENCY OF THE RECEIVER BANDPASS FOR THE N-th VARIATE H_N = HORIZONTAL POLARIZATION (N-th VARIATE) V_N = VERTICAL POLARIZATION (N-th VARIATE)R = CORRELATION COEFFICIENT - A NUMBER LESS THAN 1 WITH PLUS OR MINUS
SIGNS AND INCLUDING ZERO

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higher frequency predictors and with those somewhat lower in frequency suggest that the higher frequency terms may be significantly affected by atmospheric constituents and may potentially be discarded, or have their importance suppressed, by the forward stepwise correlation process. Without the higher frequency predictors a correlation function with lower spatial resolution will result. Clouds and rain produce selective radiances as contrasted with black-body or graybody radiators, and because they are strongly frequency-selective, with a wavelength-to-the-fourth-power dependency, their effects correlate poorly and they tend to be suppressed in the correlation process. The forward stepwise correlation process seeks the correlative components among the subsets of predictors and rejects predictors that do not have correlative properties, or assigns very small coefficients to those predictors. Clouds, rain, antenna sidelobes, and manmade interference do not have correlative properties and all are suppressed in a manner of degree. The correlation matrix does not functionally participate in the development of the correlation function or in the imaging process. Mainly, it is importantly useful as a diagnostic and as a prognosticator of the success of the statistical processes that will ultimately produce an image.

THE CORRELATION FUNCTION

Stepwise correlation is an extremely simple process. Basically, a dependent variable, which in some correlation literature is called a criterion variable, is selected by the statistician depending upon what phenomenon he expects to observe. A higher frequency criterion variable will operate to produce a narrow spatial filter with the further expectation that shallow ice penetration depths will be observed. Suppose a distribution of new ice is to be imaged. A higher frequency criterion variable will better estimate the

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distribution of brine in the few upper centimeters of the new ice and simultaneously provide a narrow spatial filter. If greater penetration depths are desired, for any reason, then a lower frequency criterion variable is the best candidate. Penetration depth is a function of surface conductivity at any specified frequency -- it is inversely proportional to surface conductivity.

Having chosen a criterion variable, a subset of predictors is introduced into the forward stepwise correlator program. This program operates to determine in a stepwise manner the degree of correlation of all the individual predictors with respect to the criterion variable. The most highly correlated predictor is chosen first by the program. This will agree with the one shown in the correlation matrix. Then the next predictor is chosen that maximizes the combined correlation of the two predictors as they explain the thermal variations in the criterion variable. The process is continued in this stepwise manner until the correlation is no longer improved by the addition of any of the available predictors. At this point the correlator halts and assigns coefficients and other statistical properties to the participating subset of predictors that best explain the thermal variations given by the criterion variable. The correlation function is formed by the terms of the significant participating predictors and their associated coefficients. The magnitude of the coefficient assigned to each term by the stepwise correlator must not be construed to reflect its relative importance. In fact, the relative magnitudes of the coefficients are of very little analytical use at all.

The coefficients are dimensioned to compensate for differences in the digital counts for various predictors and also to allow the accumulated sum of the terms to be properly dimensioned in thermal-temperature units for ice. The

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relative significance and importance of the individual terms in the structure of the correlation function are given by the Beta coefficients for each term and will be described later.

The structure of the multivariate cross-correlation function as it is designed to estimate the thermal properties of ice is illustrated by example in Table 3.

\hat{T}_{ice} is shown to combine the terms of a forward stepwise correlation for a particular subset of variates for a sampling matrix taken over the Beaufort

Table 3
Multivariate Cross-Correlation Function

VARIATES	COEFF. OF DETERMINATION	STD. ERR. EST. (KELVINS)	BETA COEFF.
	ACCUMULATED CORRELATION	RESIDUAL ERROR, K	RELATIVE INFLUENCE
H37S	0.912	3.875	4.032
H10S	0.953	2.853	0.687
V21S	0.964	2.508	2.090
H18S	0.973	2.217	1.133
H37	0.976	2.111	2.950
V21	0.978	2.020	3.442
H6S	0.979	2.000	0.680
V6S	0.980	1.977	0.375

CRITERION VARIABLE: V37

$$\hat{T}_{ice} = a_0 + a_1(H37S) + a_2(H10S) + a_3(V21S) + a_4(H18S) + a_5(H37) + a_6(V21) + a_7(H6S) + a_8(V6S), K$$

WHERE:

$a_0 = 7.989123E+01$	$a_5 = -1.855750E-01$
$a_1 = 5.134183E-05$	$a_6 = 2.275033E-01$
$a_2 = -5.516359E-06$	$a_7 = 5.500527E-06$
$a_3 = -2.852493E-05$	$a_8 = -3.734757E-06$
$a_4 = -1.006479E-05$	

...Parenthetical symbols are post-detected output quantities in unprocessed digital counts.
Prefixed letters indicate polarization. Suffixed letter S indicates a quadratic term.

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Sea in the Arctic. The variates of the subset are listed in the order of their selection together with the corresponding accumulated correlation, residual errors, and the relative influence of each term on the estimate of \hat{T}_{ice} . The coefficients-of-determination (correlation-coefficient squared) are shown to monotonically increase as each variate is added. The total accumulated correlation is 0.98 for all variates. The difference between the coefficients-of-determination for any two adjacent variates are defined as partial correlation coefficients. The residual errors show how the successive terms reduce the residual errors with respect to the criterion variable. When either the coefficients of determination stop increasing or the residual errors stop decreasing, the stepwise correlation process is terminated and the function is finally formed for that subset of predictors. Bendel(2) treats the subject of stopping criteria as it relates to accumulated correlation and residual errors (mean-squared errors) in elaborate detail.

The relative influence of each term and its coefficient on the estimate \hat{T}_{ice} is given by the Beta coefficients, which are really partial regression coefficients in standard measure. The Beta coefficients specify the average change in the estimate for ice temperatures \hat{T}_{ice} for a one standard deviation change in the value of the variate. The Beta coefficients operate by their relative magnitudes. That is, the larger the coefficient the greater its influence on the estimate of ice temperatures. From Figure 3, the first variate may be expected to change the mean temperature T_{ice} by twice as much as the third variate, provided the changes actually occur.

New subsets of predictors may be entered into the stepwise correlator for structuring additional new functional estimates of \hat{T}_{ice} .

CONCLUSIONS

Background discussions relating the application of multivariate cross correlation to the measurement of relative ice temperatures show that the forward stepwise regression can be effectively applied to the task. The discussion material considers the involvement of the terms of the correlation function as they operate to form a narrow spatial filter. Because the width of the spatial filter is narrower than can be explained by diffraction limited apertures (but not by filter theory) the process is reasoned to form a wideband, passive, synthetic aperture which here addresses the relative temperature measurement of ice from orbit.

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- (1) N.R. Draper and H. Smith, Applied Regression Analysis. John Wiley, 1966.
- (2) R.B. Bendel, Stopping Rules in Forward Stepwise Regression (Doctoral dissertation, University of California, Los Angeles, 1973).